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BIAXIAL DEFORMATION BEHAVIOUR OF Zr-2.5 Wt% Nb PRESSURE TUBES IN VARIOUS ID/OD ENVIRONMENTS AT LOW INTERNAL PRESSURES AND ELEVATED TEMPERATURES

Report No 86-173-K
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ABSTRACT

A series of biaxial tests have been carried out to determine the critical combinations of internal pressure and temperature required to suppress significant ballooning in Zr-2.5 Nb PT's at elevated temperatures in a steam environment. Results obtained indicate that for temperatures in the range 1273-1410 K, the critical pressure should lie in the range 0.25-0.3 MPa. Detailed analyses of experimental data indicate that several factors contribute to strengthen the Zr-2.5 Nb PT material when it is heated above about 1173 K. These factors include a phase transformation, a morphological change in microstructure and oxygen-strengthening. The data also showed that the difference in deformation behaviour between testing in ID/OD steam/argon and steam/CO_2 environments is marginal. Results obtained from testing at about 1600 K, the highest temperature investigated, indicated that a differential internal pressure of 0.3 MPa was still too high to suppress significant ballooning.

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EXECUTIVE SUMMARY

Biaxial Deformation Behaviour of Zr-2.5 Wt% Nb Pressure Tubes in Various ID/OD Environments at Low Internal Pressures and Elevated Temperatures

E.T.C. Ho and A. Donner
Materials Integrity Section
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Objective: The principal goals of the test program were to determine what critical combinations of internal pressure and temperature are required to suppress significant biaxial deformation at elevated temperatures and to determine more quantitatively the effect of oxidation on elevated temperature deformation behaviour.

Major Results of Study:

1. For test temperatures in the range 1273-1410 K, the critical pressure for suppression of significant ballooning lies in the range 0.25-0.3 MPa.

2. The factors which contribute to enhance the PT material's resistance to deformation above about 1173 K include: (a) change in crystal structure from hcp to bcc; (b) change in grain morphology from fine lamellar to coarse equiaxed; (c) oxygen strengthening associated with oxidation of the PT material. For the test conditions investigated, factors (a) and (b) appear to have a much larger influence on strengthening than factor (c).

3. At a test temperature of about 1600 K, a differential internal pressure of 0.3 MPa was still too high to suppress significant ballooning.

4. The difference in deformation between testing in ID/OD steam/argon and steam/CO_2 environments is marginal.

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TO: Dr. R.A. Brown
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Nuclear Studies & Safety Dept

Biaxial Deformation Behaviour of Zr-2.5 Wt% Nb Pressure Tubes in Various ID/OD Environments at Low Internal Pressures and Elevated Temperatures

1.0 INTRODUCTION

Test results obtained from a small program/1/ funded by NSSD carried out at Ontario Hydro Research indicated that an internal pressure of 0.25 MPa was insufficient to cause significant deformation when the Zr-2.5 Nb PT samples were heated above about 1173 K in an internal steam environment. Detailed analyses of the experimental data showed that a very large fraction of the diametral expansion occurred over the temperature range 900-1173 K when the samples were ramped at 3 K/s from about 573 K to the upper hold or peak temperatures. The deformation behaviour at the upper hold temperatures indicated that the combined effects of oxygen strengthening, changes in crystal structure and changes in grain morphology had significantly enhanced the materials resistance to deformation. However, since only a limited number of tests were carried out, it was not possible to determine what critical combinations of internal pressure and upper hold temperature were required to slow down or significantly suppress the biaxial expansion.

In view of the above, the present test program was proposed and subsequently approved by the "Fuel Channel High Temperature Transients" working party of the AECL-OH CANDEV program. The main objectives of the test program were as follows:

1. determine what critical combinations of internal pressure and temperature are required to suppress significant biaxial expansion at elevated temperatures in a steam environment;

2. determine more quantitatively the effect of oxidation on elevated temperature deformation behaviour;

3. increase the database available for verification of existing computer codes which are needed for LOCA analyses.

The above information is required to quantify the full range of conditions over which pressure tube ballooning can occur in postulated accidents. Since ballooning can lead to the moderator acting as an efficient heat sink, it is important to know when this heat sink can be credited in the analysis for an arbitrary accident scenario.

2.0 EXPERIMENTAL

The biaxial tests were carried out using the Biaxial Test Facility (BTF) developed at Ontario Hydro Research. A detailed description of the BTF has been given elsewhere/2,3/ and will not be repeated here. Only a few minor modifications to the BTF had to be made in order to meet the particular present test requirements. Briefly, the test specimens were fabricated using 0.6 m lengths of Zr-2.5 Nb PT material. Titanium flanges were welded to both ends of the PT sections to enable internal pressurization of the test piece. Seven out of the eight samples were instrumented with twelve ISA type-K thermocouples (TC's) for temperature control and measurement. The TC used for closed-loop temperature control, via the custom-built induction heating system, was located at the top (0^{o} mark) and middle of the test piece. Eights TC's equally spaced around the tube circumference, starting at the top location, were spot welded to the mid-section of the test sample. The remaining three TC's were located about 5 cm from the first nine and were spot welded equally spaced around the circumference starting at the 0^{o} location. The eighth sample was instrumented with only four type-K TC's equally spaced around the tube circumference starting at 0^{o} location. To prevent the formation of low-temperature melting point eutectics between the TC wires and the Zr-based specimen, 75 μm thick platinum spacer pads were interposed between the test piece and the bare TC beads. This technique of protecting the TC beads was used only when the test temperature was less than about 1420 K. Above this temperature, 50 μm thick iridium (Ir) pads were used.

Five tests were performed using argon for the cover gas (containment vessel atmosphere). The last three tests were carried out using CO_2 for cover gas. Seven tests were carried out under closed-loop control of the specimen temperature using a feedback signal obtained from the TC located at the 0^{o} location. The last test was conducted under manual control of the power output of the induction heating system. This procedure was necessitated because the desired hold temperature of 1573 K was

beyond the range of the programmable temperature controller of the induction heating system. As in previous tests, pressure control was achieved through the use of the feed-and-bleed pressure circuit of the BTF. Steam was generated in-situ by placing appropriate amounts of distilled water inside the test specimen.

In a given test, the sample was heated from ambient temperature to about 573 K and then maintained at this lower hold temperature for a predetermined length of time which ranged from 40 to 280 s. Following this lower hold or normalizing period, the sample was ramped at a desired heating rate (generally constant) to preselected upper hold temperatures in the range 1273-1600 K. At the termination of the temperature ramping, the specimen was held at the upper hold temperature for a preprogrammed length of time which can be up to 600 s. Upon completion of the upper temperature hold, the power to the induction heating system was turned off and the internal pressure was discharged via a solenoid dump valve. Both the specimen internal pressure and the containment vessel pressure were recorded as a function time, along with the LVDT and temperature indicator outputs.

3.0 RESULTS

3.1 General

Photographs illustrating the general appearance of the deformed specimens are presented in Figure 1. The plane of the photographs is parallel to the 0^{o}-180^{o} (top-bottom) diametral plane of the specimens. Figure 1 shows clearly that the heated zone of the test specimens (~35 cm's in length) deforms approximately uniformly until average circumferential strains well in excess of 0.1 were attained. Blow-ups showing the nature of the outer surface of specimens deformed to very large circumferential strains are presented in Figure 2. Severe cracking of the outer surface at large strains is evident. The appearance of the small through-wall crack in test sample BTC023 is shown in Figure 2(c).

3.2 Tests Using Argon for Pressurization and Argon for Cover Gas

Plots illustrating the variation of internal pressure, selected temperatures and average circumferential strain as a function of time for the two tests carried out in completely argon environments are shown in Figures 3 and 4. The two sets of strain vs time curves show clearly that there is a dramatic decrease in deformation rate when the PT samples were heated above about 1173 K. Figure 5 presents temperature vs time plots which illustrate in detail the circumferential temperature variation (shown partially in Figure 4) in the immediate vicinity of strain

measurement. The data show that the maximum temperature difference between any two monitored positions on the specimen mid-section circumference was about 30 K during the temperature ramping phase of the experiment.

3.3 Tests Using Steam for Pressurization and Argon for Cover Gas

Plots illustrating the variation of internal pressure, selected temperatures and average circumferential strain as a function of time for the three tests carried out in argon cover gas using steam generated in-situ for internal pressurization are presented in Figures 6-8. The three sets of strain data also show that there is a dramatic decrease in strain rate when the specimens were heated above about 1173 K, consistent with the data shown in Figure 3 and 4. Comparison between data presented in Figures 6 and 7 indicates that increasing the internal pressure from about 0.31 MPa to 0.36 MPa increases the deformation rate significantly. Likewise, the data presented in Figures 7 and 8 indicate that increasing the hold temperature from 1273 K to 1373 K also increases the rate of ballooning. The complete set of temperature vs time plots presented in Figure 9 show that the circumferential temperature gradient decreases as the sample was heated from about 573 K to the upper hold temperature of about 1273 K. The data also indicate that two of the temperature channels, labeled 6 and 7 in the figure, had deteriorated to some degree. The large ripples observed in these two channels were not genuine temperature variations, but were the result of noise pick-up from the induction heating system.

3.4 Tests Using Steam for Pressurization and Carbon Dioxide for Cover Gas

Plots illustrating the variation of internal pressure, selected temperatures and average circumferential strain as a function of time for the three tests carried out in CO_2 cover gas are presented in Figures 10-12. The strain data presented also indicate that there is a considerable decrease in deformation rate when the PT samples were heated above about 1173 K. However, the strain data presented in Figures 11 and 12 also show that when only a small part of the tube circumference is above 1173 K, the observed decrease in strain rate is much less dramatic than the case when the entire tube circumference is heated above 1173 K. It should be noted here that the strain data presented in Figures 11 and 12 become unreliable after a certain point in time. In test BTC022, (Figure 11), we deduced that the quartz fibre-LVDT strain measurement system began to malfunction after about 450 s into the test, since the LVDT core essentially stopped moving shortly after the above point in time. From the value of the average circumferential strain obtained from a post-

test measurement using π-tape, we estimate that the strain curve should follow the dashed line drawn in the figure. From a detailed analysis of the strain data presented in Figure 12, we concluded that the strain data become unreliable after about 380 s into the test. When the quartz fibre is heated above about 1420 K, it becomes very weak and as a result, it stretches very easily. Consequently, the movement of the LVDT core no longer reflects the true increase in the tube diameter or circumference thereby greatly underestimating the real average circumferential strain. The complete set of temperature vs time data presented in Figures 13 and 14 show vividly that the circumferential temperature gradients were extremely large during the temperature ramping phase of these tests. Furthermore, the data in Figure 14 also showed that the life of type K TC's is very short at temperatures above 1573 K.

4.0 DISCUSSION OF RESULTS

4.1 Deformation Behaviour in Completely Argon Environments

Results obtained from biaxial tests carried out previously/1-4/ indicate that testing in a wholly argon environment represents the optimum condition for characterizing the biaxial deformation behaviour in the BTF. The use of argon for the pressurizing medium and the containment vessel cover gas facilitates good control of the specimen internal pressure via the feed-and-bleed circuit and also enables minimum circumferential temperature gradients to be obtained during both the temperature ramping and temperature hold phases of the testing. It should also be pointed out here that well-characterized specimen temperature and internal pressure data allow the corresponding strain data to be analysable in much more quantitative detail.

As shown in Figures 3 and 4, the strain vs time curves show a dramatic drop in strain rate when the PT samples were heated above 1173 K. Such deformation behaviour has been observed previously in both uniaxial/5,6/ and biaxial/1,3,7/ tests. The significant reduction in deformation rates observed has generally been attributed to the formation of an equiaxed β-Zr phase. This transformation occurs when the Zr-2.5 Nb PT material is heated above its $\alpha + \beta \rightarrow \beta$ transus temperature of about 1173 K/8/.

Once the specimens are heated to and held at the upper hold temperatures, the experimental conditions are such that the testing is essentially that of a biaxial creep test. Blow-ups of the curves presented in Figures 3 and 4, in Figures 15 and 16 indicate that the strain data have the general shape of a classical uniaxial creep curve. The strain curve shown in Figure 15 exhibits both a secondary and a tertiary creep region.

In contrast, the biaxial creep curve in Figure 16 exhibits the three principal regimes of primary, secondary and tertiary creep.

The strain data presented in Figures 3 and 4 should constitute a good database for assessing more quantitatively the accuracy of the WNRE creep correlations reported by Shewfelt et al/7/, for temperatures above 1173 K. Since the WNRE creep correlations were formulated using data obtained from uniaxial creep tests carried out in a high-purity argon atmosphere, the use of a wholly argon gas environment in the biaxial tests should be appropriate for making detailed comparisons between the biaxial data and the WRNE creep correlation predictions.

4.2 Deformation Behaviour in Internal Steam Atmospheres with Argon Cover Gas

As outlined in previous reports/2-4/, one of the consequences of placing distilled water inside the test specimens for generating steam in-situ is that significant circumferential temperature gradients are developed during the temperature ramping phase of the test. This experimental complication implies that it is very difficult to compare quantitatively results obtained from tests in wholly argon environments and test in steam/argon environments during the temperature ramping phase of the experiment. However, during the temperature hold phase of the tests, the circumferential temperature gradients are comparable in the above-mentioned two test environments. Thus, during the elevated temperature hold, the test results may be compared quantitatively to assess the effect of an internal steam environment on the biaxial deformation behaviour.

Detailed comparisons of test data obtained in argon/argon and steam/argon environments are presented in Figures 17 and 18. The data in Figure 17 show clearly that for an internal pressure of 0.3 MPa and a hold temperature of 1273 K, the deformation rate is significantly slower in the steam/argon environment. However, for test times up to about 640s, the two strain curves are virtually identical. The above is observed because the circumferential temperature gradients were comparable during the entire temperature ramping phase in the two tests. For times greater than 640 s, the two strain curves begin to diverge considerably. In contrast, the data presented in Figure 18 show that the two strain curves are quite different throughout the entire time frame of comparison. For times up to about 280 s, the test carried out in an argon/argon environment (BTYZ) produced higher average circumferential strains, although it was at a slightly lower internal pressure than the test in steam/argon (BTNO). This observation results because the entire circumference at the strain measurement location in test sample BTYZ was very close to the preprogrammed temperatures. However, for test sample BTNO,

this was clearly not the case. For times greater than about 280 s, all deforming regions of test sample BTYZ were above 1173 K. As a results, a large decrease in deformation rate is observed and the reason for this observation has been discussed earlier. During the time interval 280-320 s, a large fraction of test sample BTNO was still below 1173 K. Consequently, the observed deformation rates were still very high. For times greater than 320 s, all deformation zones in test sample BTNO were above 1173 K and the observed deformation behaviour can easily be rationalized with the earlier explanation of reduction in strain rates above 1173 K. The comparison also shows that for times greater than about 350 s, the two internal pressures were approximately equal. For times greater than about 320 s, the strain data show clearly that sample BTYZ was deforming at a much higher rate than sample BTNO. However, it should be noted here that the bottom temperature of sample BTNO was about 30 K lower than that of sample BTYZ during the temperature hold.

The data presented in Figures 6-8 indicate that the critical value of internal pressure needed to suppress significant ballooning for hold temperature in the range 1273-1373 K is less than about 0.3 MPa. However, the current test data also indicate that for pressures in the range 0.3 to 0.4 MPa, it still requires from 400 to 500 s at temperature before "contact" circumferential strains (~0.18) are produced.

For tests BTUV, BTWX and BTXY, 10, 20 and 25 ml's of distilled water were placed inside the test samples for generation of steam in-situ. The above volumes of water represent several times the volumes needed to produce the desired experimental steam pressures. However, some of the steam was vented out through the feed-and-bleed pressure control circuit and some of it was consumed in the oxidation of the test piece. For the above relatively low volumes of water used, we cannot be absolutely sure that some of the tests were not operating under steam starvation conditions towards the latter periods of the temperature holds. Since the experimental procedure entails complete depressurization of the specimen at the end of the test, we believe that most of the residual steam inside the test price would be expelled by this action. However, if we were deforming under steam starvation conditions, the deformation rates observed would be higher than those obtainable under saturated steam conditions. Therefore, use of the present rates to predict contact times would be slightly conservative.

The comparison of results presented in Figure 19 indicates that an increase of about 0.05 MPa has a noticeable effect on the deformation behaviour at a test temperature of 1273 K. At an internal differential pressure of 0.31 MPa, the initial deformation rate at 1273 K was about 5.9×10^{-5} s^{-1}. By increasing the

internal pressure to 0.36 MPa, the initial deformation rate at 1273 K was increased to about 1.5×10^{-4} s^{-1}, about a three-fold increase above that at the lower pressure. However, it should be noted here that the average temperature of the sample at the higher internal pressure was slightly higher than that of the lower pressure sample. To assess the above difference more quantitatively, the test data must be compared in much greater detail, which is beyond the scope of the present report.

4.3 Deformation Behaviour in Internal Steam Atmospheres with CO_2 Cover Gas

Since the annulus gas in current CANDU power reactors is carbon dioxide (CO_2), NSSD personnel stipulated/9/ that the majority of the biaxial tests should be carried out using CO_2 for cover gas in the BTF. However, because approval for the test program was delayed significantly, by the time we were ready to commence testing the above request had been superseded by another NSSD document/10/. Unfortunately, this second document did not reiterate the use of CO_2 cover gas and as a result, only the last three tests were carried out using CO_2 for cover gas. Furthermore, the experimental conditions chosen for these three tests were sufficiently different from those chosen for steam/argon environments that a quantitative assessment of the difference in deformation behaviour between testing in argon and CO_2 cover gases cannot be made. However, the comparison of test data presented in Figure 20 indicates that there are no large differences in deformation behaviour in argon and CO_2 cover gases. The higher rates observed for test BTC021 can be attributed to its slightly higher internal pressure.

As indicated in Figure 11, a differential internal pressure of 0.3 MPa was insufficient to produce relatively high ballooning rates at a hold temperature of about 1373 K. The observed initial strain rate of about 6.3×10^{-5} s^{-1}, on achieving a steady-state circumferential temperature gradient, is more than twenty times higher than that observed at 1405 K and 0.25 MPa reported previously/1/. On the other hand, the above initial rate is about three times lower than that observed at about 0.35 MPa and 1373 K. The above results indicate quite clearly that to suppress significant ballooning at 1373 K, the internal pressure should lie in the pressure range 0.25-0.3 MPa.

As mentioned earlier, the last test carried out for the current test program was done under manual control of the induction heating system. This action was necessitated because the temperature range of the closed-loop heating system temperature controller was only 273-1473 K. The data in Figures 12 and 14 show clearly that the life of type K TC's above 1573 K is very short. For,

although the four TC's were protected from interalloying with the Zr-2.5 Nb sample by Ir pads, none of them lasted the duration of the test.

Close scrutiny of the test data indicated that the sample ruptured at about 558 s into the test. The rupture location was at about the 270° location where the tube was at the highest temperature (estimated to be about 1610 K). Photographs illustrating the nature of the rupture site and the appearance of the surrounding PT material are presented in Figures 2(b) and 2(c). The rupture was in the form of a small axial crack. Figure 2(c) shows clearly that there are numerous partial through-wall axial cracks on the outer surface of the deformed specimen. There is also evidence that the hot zone had just touched the ID bore of the induction heating coil which was separated from the test specimen by a piece of Fiberfrax Paper. Post-test measurements indicate that the average circumferential strain at rupture was about 0.285, well above the theoretical contact strain of 0.18. The appearance and size of the through-wall crack also indicate that a differential pressure of 0.3 MPa was too low to have much of a driving force for crack extension at the test conditions investigated.

5.0 CONCLUSIONS

1. Tests carried out in wholly argon environments confirmed that there is a large decrease in deformation rate when the PT specimens were heated above the $\alpha + \beta \rightarrow \beta$ transformation temperature for the Zr-2.5 Nb alloy.

2. Test data obtained from testing in wholly argon environments should provide a good database suitable for rigorous assessment of the WNRE creep correlations reported by Shewfelt et al.

3. The shape of the average circumferential strain vs time curve obtainable from a biaxial creep test is similar to that obtainable from an uniaxial creep test. The biaxial creep curve generally exhibits primary, secondary and tertiary creep regimes.

4. Detailed comparisons of experimental data obtained from testing in argon/argon and steam/argon test environments indicate that there is additional strengthening of the PT material when the deformation occurs in a steam environment. However, this additional strengthening is not as great as that associated with the transformation to a completely β-phase material.

5. Experimental data obtained indicate that the critical pressure needed to suppress significant ballooning in an internal steam environment is in the range 0.25 - 0.3 MPa for test temperatures in the range 1273-1410 K.

6. Detailed comparisons of data obtained from testing in steam/argon and steam/CO_2 environments indicate that there were no significant differences in deformation behaviour in these two environments.

7. Data obtained from a test carried out in a steam/CO_2 environment at about 1600 K indicate that a differential internal pressure of 0.3 MPa was still too high to suppress significant ballooning of Zr-2.5 Nb PT material.

8. Test data obtained in the test program increase the database available for assessment of high temperature deformation computer codes used in reactor safety analyses of CANDU power reactors.

ACKNOWLEDGEMENTS

The authors wish to thank Mr. G.H. Archinoff and Dr. P.S. Kundurpi of the Nuclear Studies and Safety Department of the Design and Development Division for valuable discussions and inputs in establishing appropriate test conditions for the tests carried out. We are also grateful to AECL-RC, WNRE and the Nuclear Studies and Safety Department for encouragement and financial support under the COG-CANDEV development program.

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REFERENCES

1. Ho, E.T.C. and Donner, A., Ontario Hydro Research Division Report No 84-381-K, February 11, 1985.

2. Ho, E.T.C. and Donner, A., Ontario Hydro Research Division Report No 83-18-K, February 2, 1983.

3. Ho, E.T.C. and Donner, A., Ontario Hydro Research Division Report No 84-100-K, May 4, 1984.

4. Ho, E.T.C. and Donner, A., Ontario Hydro Research Division Report No 85-243-K, September 10, 1985.

5. Ho, E.T.C. and McGraw, M.J., Ontario Hydro Research Division Report No 80-434-K, November 13, 1980.

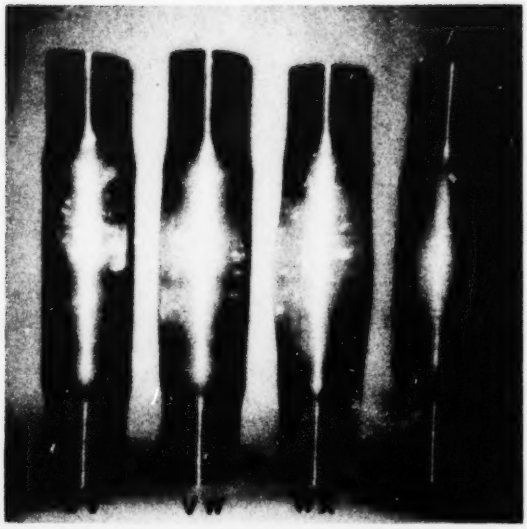
6. Ho, E.T.C. and McGraw, M.J., Ontario Hydro Research Division Report No 82-382-K, September 17, 1982.

7. Shewfelt, R.S.W., Lyall, L.W. and Godin, D.P., J. Nucl. Mater., 125, 228 (1984).

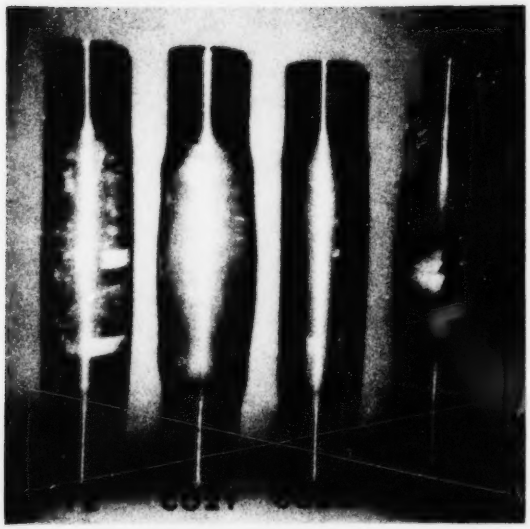
8. Hunt, C.E.L. and Foote, D.E., "High Temperature Strain Behaviour of Zircaloy-4 and Zr-2.5 Nb Fuel Sheaths, "Zirconium in the Nuclear Industry, ASTM STP 633, A.L. Lowe, Jr and G.W. Parry, Eds., American Society for Testing and Materials, 1977, pp 50-65.

9. Archinoff, G.H., Nuclear Studies and Safety Department, Design and Development Division - private communication.

10. Kundurpi, P.S., Memorandum to A.P. Muzumdar, "Suggested Test Conditions for OHRD Biaxial Tests", NSSD, File 906-N-3500P, October 17, 1985.



(a)



(b)

FIGURE 1: PHOTOGRAPHS ILLUSTRATING THE GENERAL APPEARANCE OF ALL THE DEFORMED TEST SPECIMENS. NOTICE THAT ONLY SAMPLE C023 WAS TESTED TO RUPTURE.

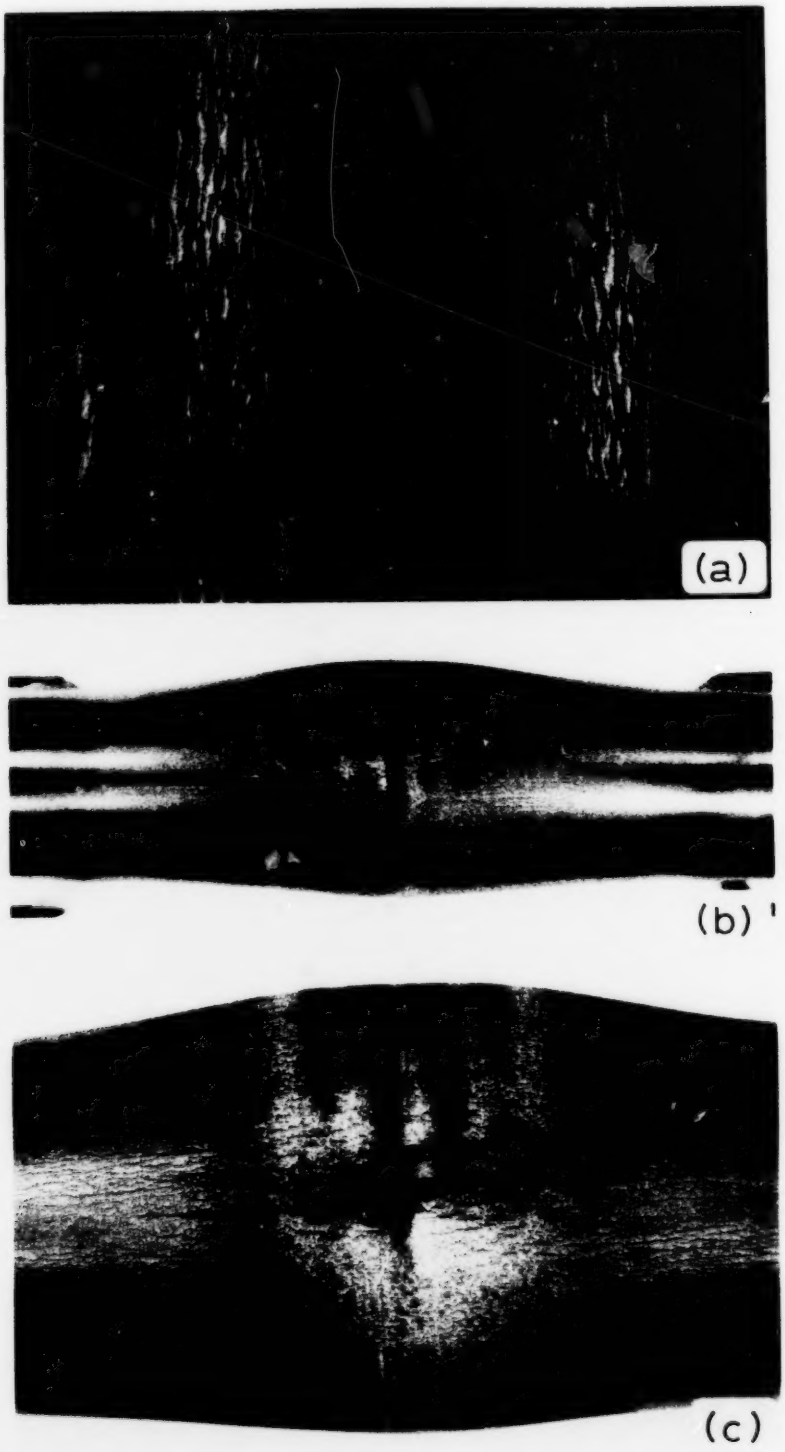


FIGURE 2: PHOTOGRAPHS OF TWO HIGHLY DEFORMED SPECIMENS SHOWING: A) SEVERE AXIAL CRACKING IN SAMPLE WX; B) A PARTIAL THROUGH-WALL CRACK IN SAMPLE C023; C) A THROUGH-WALL CRACK IN SAMPLE C023.

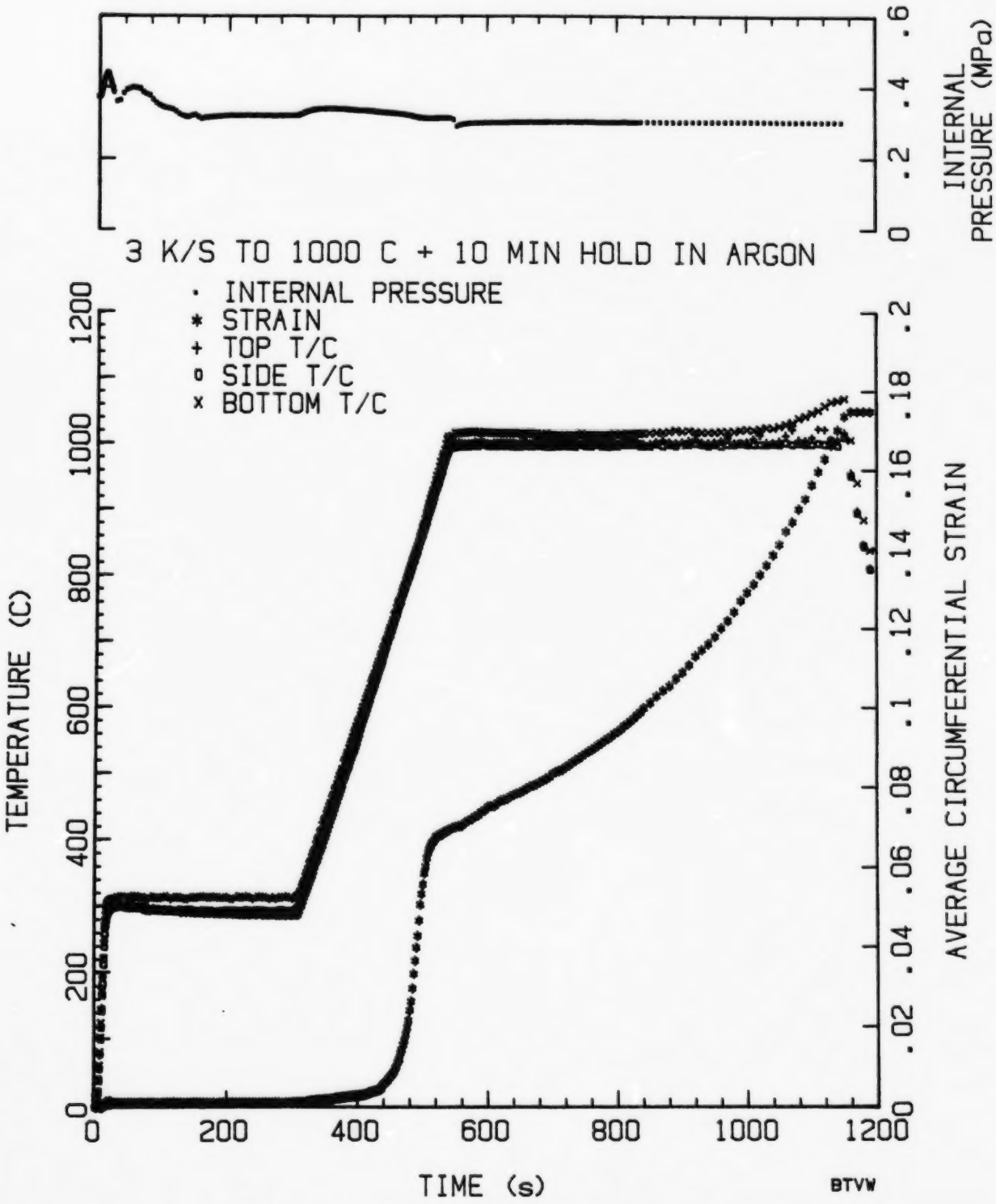


FIGURE 3: PLOTS ILLUSTRATING THE VARIATION OF INTERNAL PRESSURE, SELECTED TEMPERATURES AND AVERAGE CIRCUMFERENTIAL STRAIN AS A FUNCTION OF TIME. THE TEST ENVIRONMENT WAS ARGON/ARGON (ID/OD).

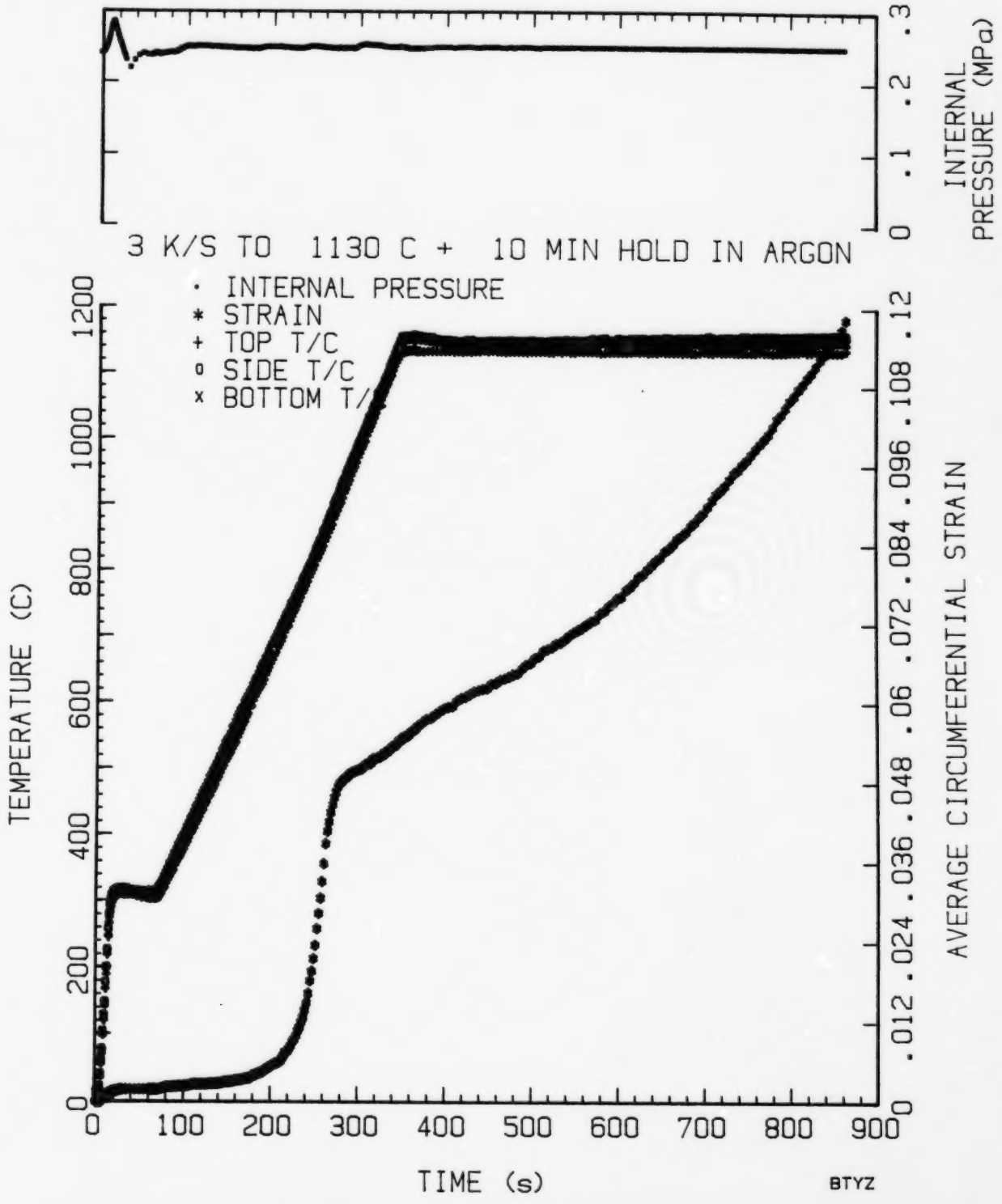

3 K/S TO 1130 C + 10 MIN HOLD IN ARGON
INTERNAL PRESSURE (MPa)
0 .1 .2 .3
· INTERNAL PRESSURE
* STRAIN
+ TOP T/C
o SIDE T/C
x BOTTOM T/
TEMPERATURE (C)
0 200 400 600 800 1000 1200
AVERAGE CIRCUMFERENTIAL STRAIN
0 .012 .024 .036 .048 .06 .072 .084 .096 .108 .12
0 100 200 300 400 500 600 700 800 900
TIME (s)
BTYZ

FIGURE 4: PLOTS ILLUSTRATING THE VARIATION OF INTERNAL PRESSURE, SELECTED TEMPERATURES AND AVERAGE CIRCUMFERENTIAL STRAIN AS A FUNCTION OF TIME. THE TEST ENVIRONMENT WAS ARGON/ARGON (ID/OD).

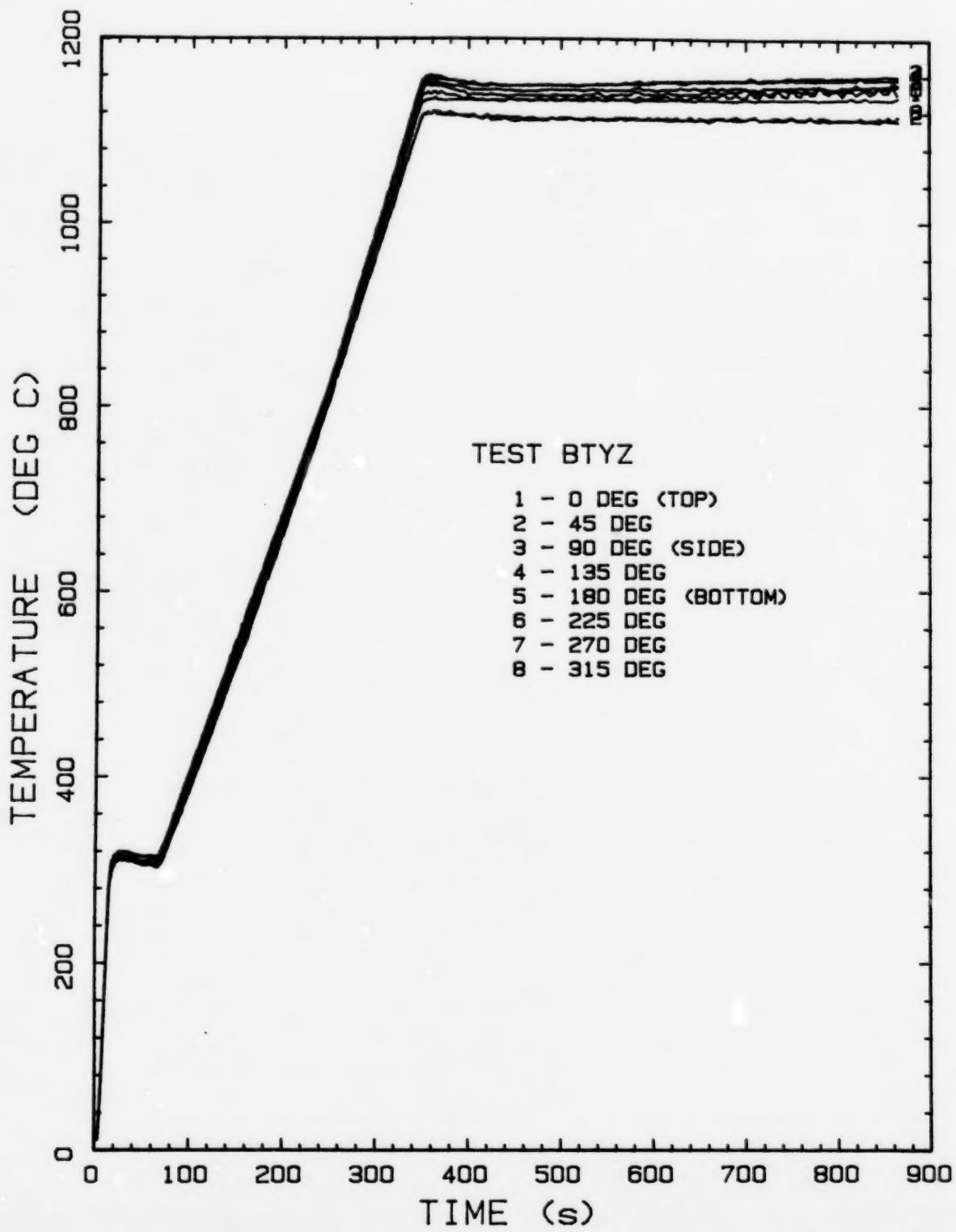


FIGURE 5: PLOTS SHOWING THE DEVELOPMENT OF THE CIRCUMFERENTIAL TEMPERATURE GRADIENT WITH TIME IN THE IMMEDIATE VICINITY OF STRAIN MEASUREMENT IN DETAIL IN TEST BTYZ.

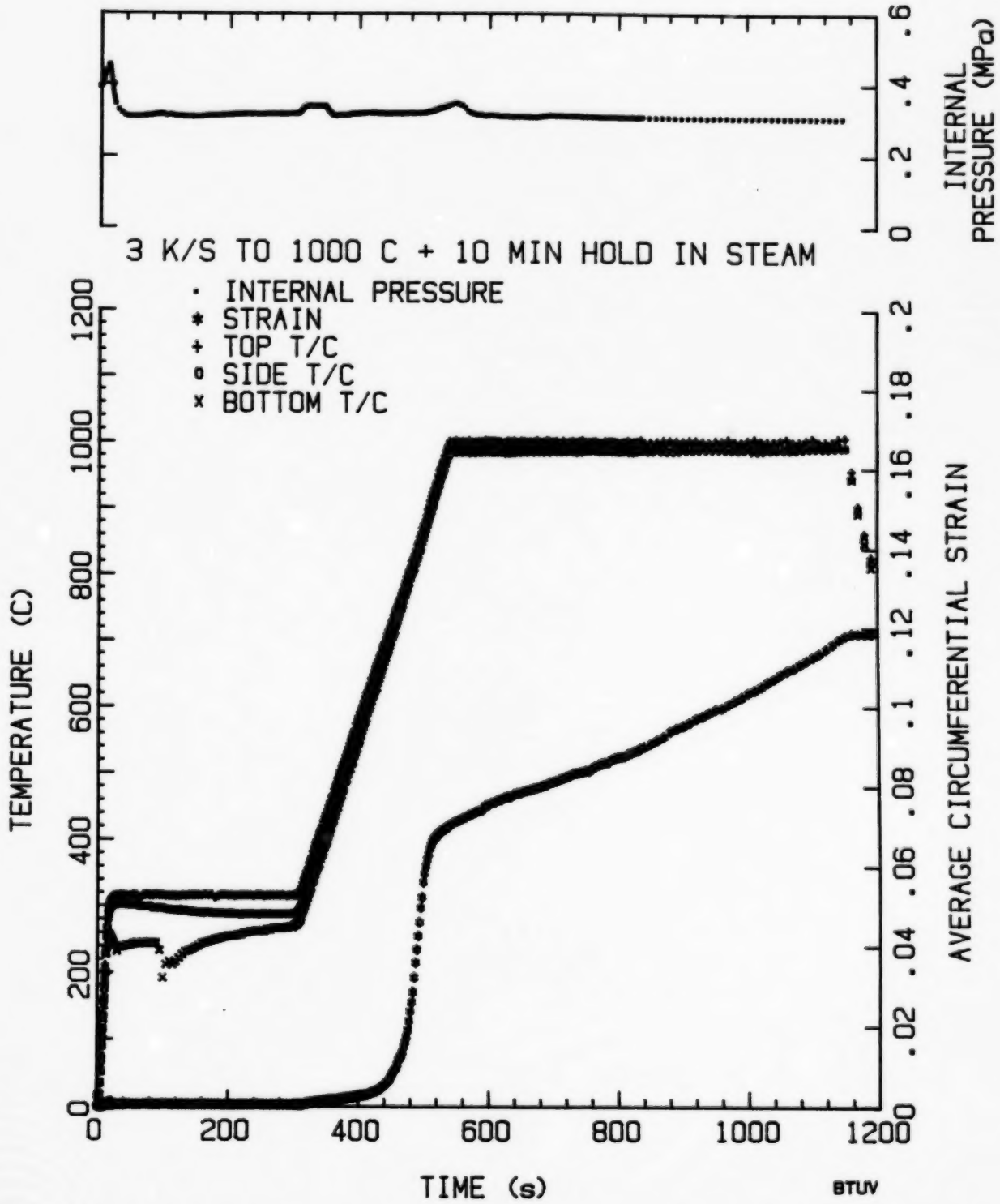


FIGURE 6: PLOTS ILLUSTRATING THE VARIATION OF INTERNAL PRESSURE, SELECTED TEMPERATURES AND AVERAGE CIRCUMFERENTIAL STRAIN AS A FUNCTION OF TIME. THE TEST ENVIRONMENT WAS STEAM/ARGON (ID/OD).

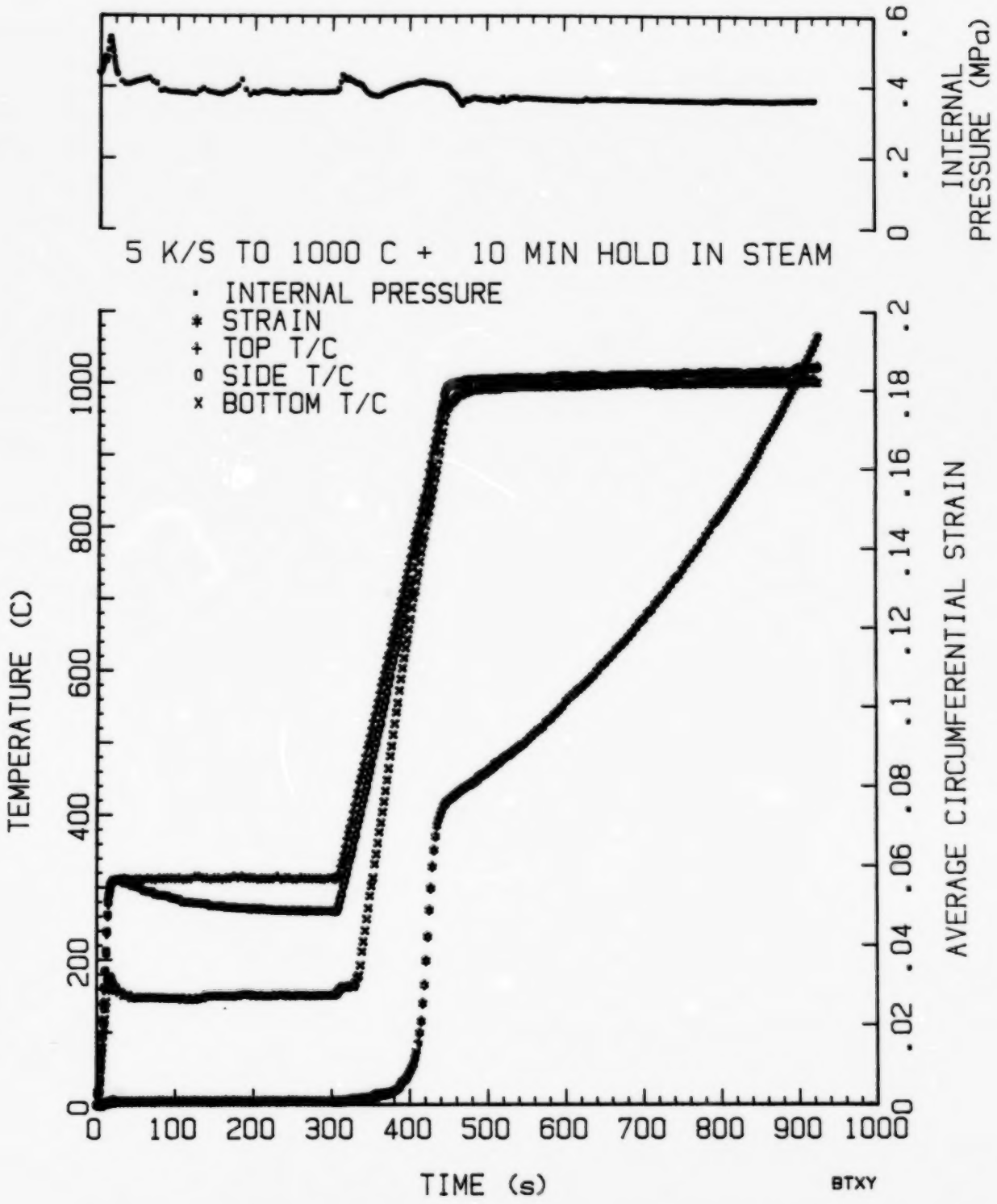

5 K/S TO 1000 C + 10 MIN HOLD IN STEAM
INTERNAL PRESSURE
STRAIN
TOP T/C
SIDE T/C
BOTTOM T/C
INTERNAL PRESSURE (MPa)
0 .2 .4 .6
TEMPERATURE (C)
0 200 400 600 800 1000
AVERAGE CIRCUMFERENTIAL STRAIN
0 .02 .04 .06 .08 .1 .12 .14 .16 .18 .2
0 100 200 300 400 500 600 700 800 900 1000
TIME (s)
BTXY

FIGURE 7: PLOTS ILLUSTRATING THE VARIATION OF INTERNAL PRESSURE, SELECTED TEMPERATURES AND AVERAGE CIRCUMFERENTIAL STRAIN AS A FUNCTION OF TIME. THE TEST ENVIRONMENT WAS STEAM/ARGON (ID/OD).

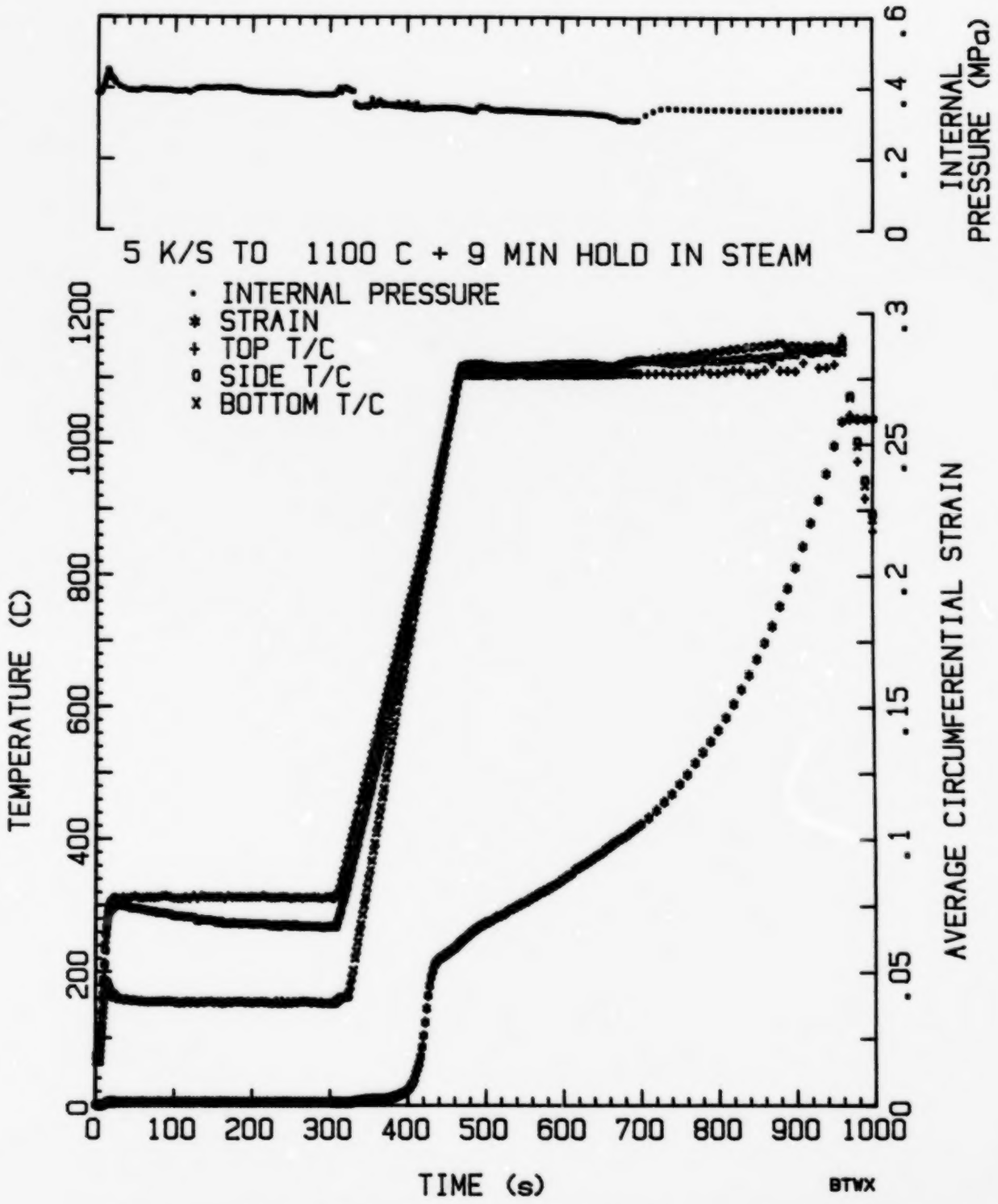

5 K/S TO 1100 C + 9 MIN HOLD IN STEAM
· INTERNAL PRESSURE
* STRAIN
+ TOP T/C
o SIDE T/C
× BOTTOM T/C
INTERNAL PRESSURE (MPa)
0 .2 .4 .6
TEMPERATURE (C)
0 200 400 600 800 1000 1200
AVERAGE CIRCUMFERENTIAL STRAIN
0 .05 .1 .15 .2 .25 .3
0 100 200 300 400 500 600 700 800 900 1000
TIME (s)
BTWX

FIGURE 8. PLOTS ILLUSTRATING THE VARIATION OF INTERNAL PRESSURE, SELECTED TEMPERATURES AND AVERAGE CIRCUMFERENTIAL STRAIN AS A FUNCTION OF TIME. THE TEST ENVIRONMENT WAS STEAM/ARGON (ID/OD).

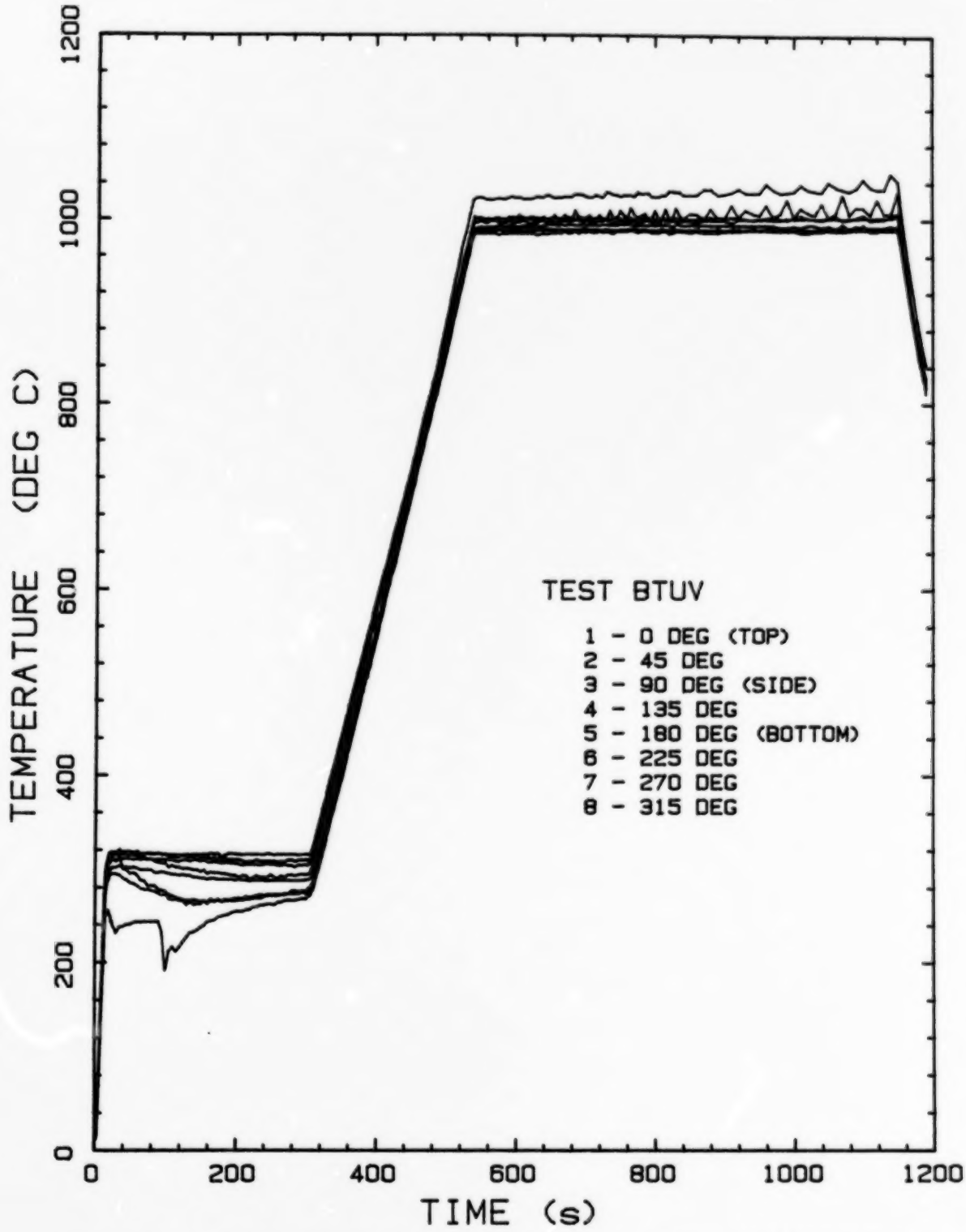


FIGURE 9. PLOTS SHOWING THE DEVELOPMENT OF THE CIRCUMFERENTIAL TEMPERATURE GRADIENT WITH TIME IN THE IMMEDIATE VICINITY OF STRAIN MEASUREMENT IN DETAIL IN TEST BTUV.

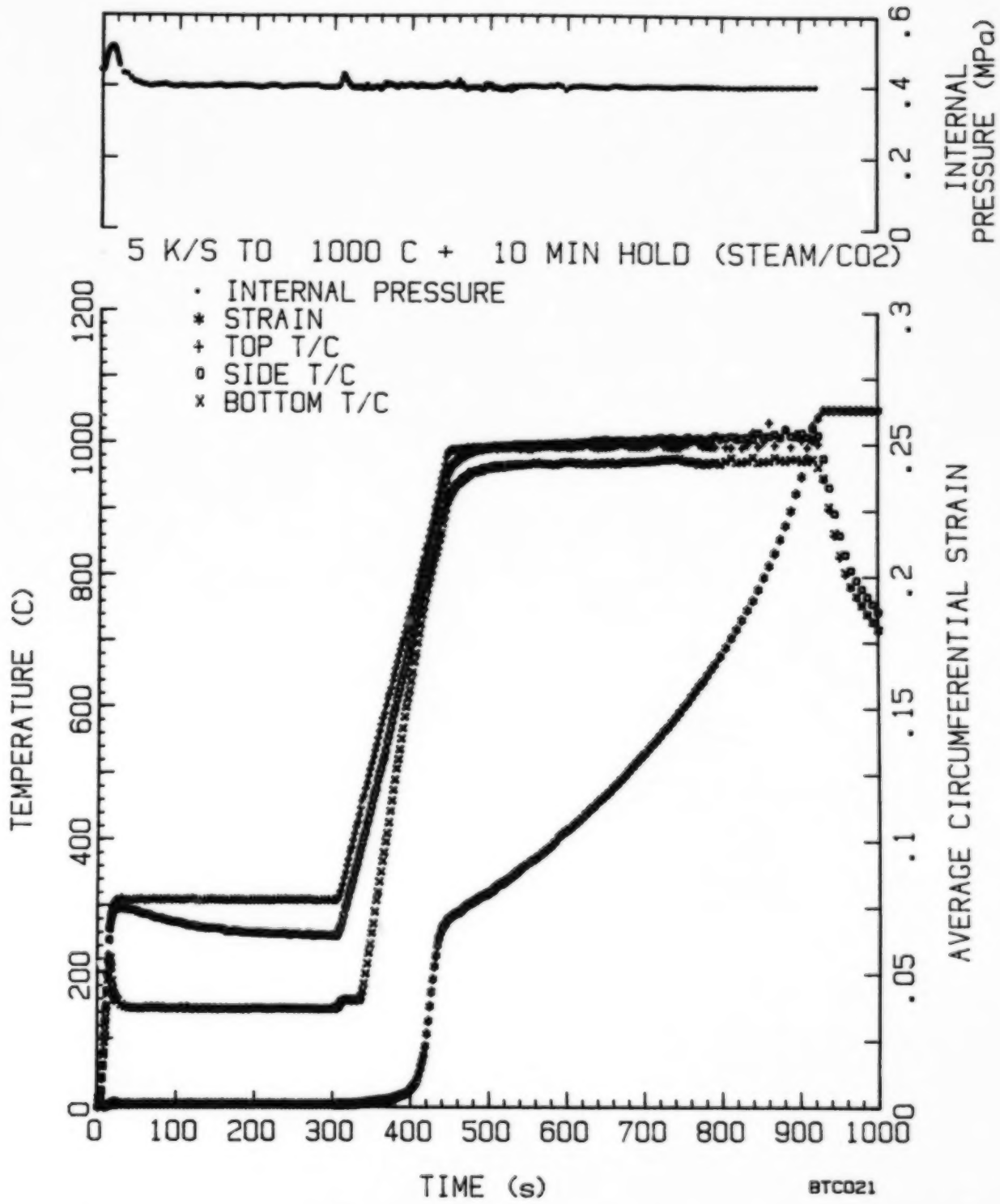


FIGURE 10: PLOTS ILLUSTRATING THE VARIATION OF INTERNAL PRESSURE, SELECTED TEMPERATURES AND AVERAGE CIRCUMFERENTIAL STRAIN AS A FUNCTION OF TIME. THE TEST ENVIRONMENT WAS STEAM/CARBON DIOXIDE (ID/OD).

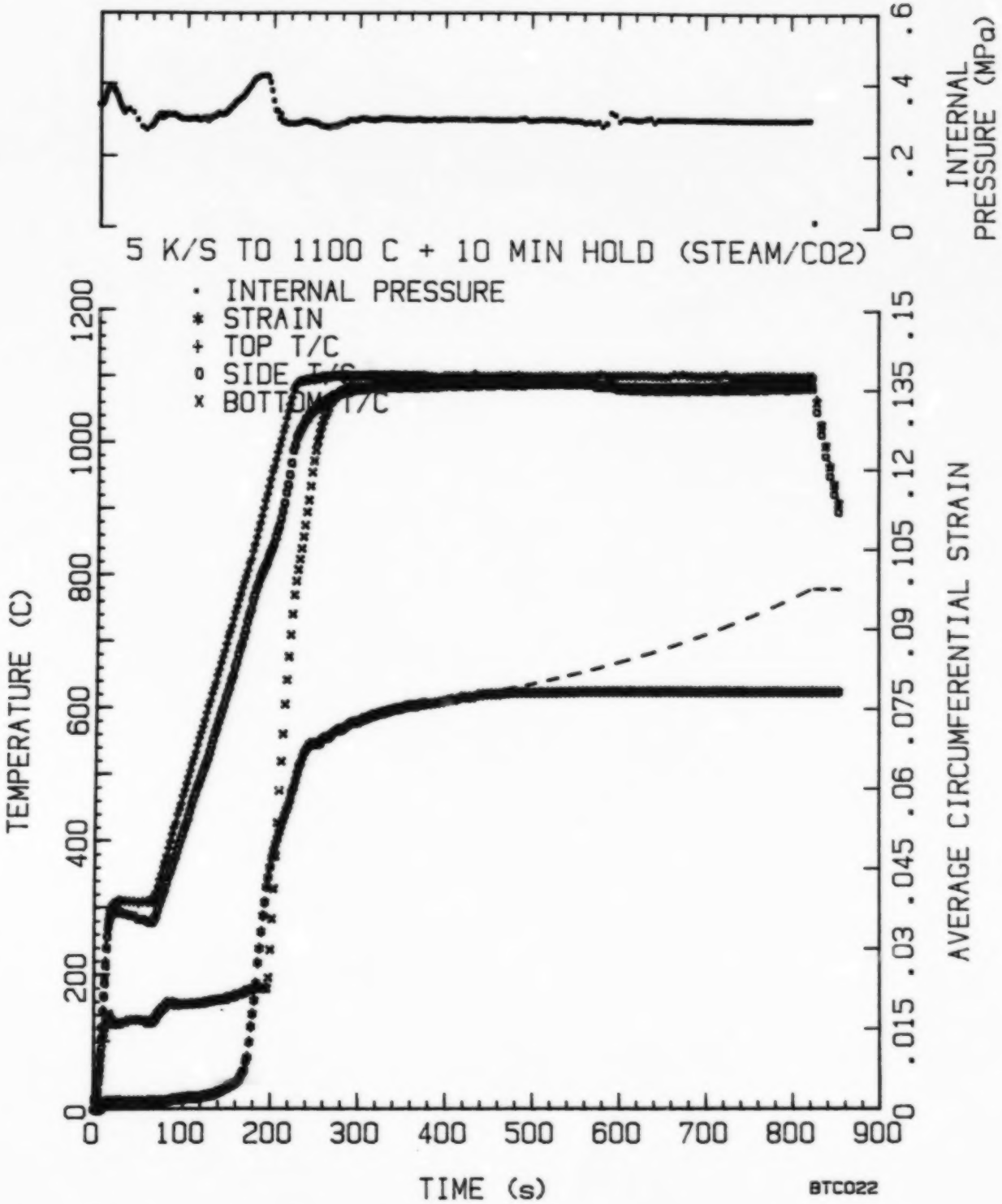


FIGURE 11: PLOTS ILLUSTRATING THE VARIATION OF INTERNAL PRESSURE, SELECTED TEMPERATURES AND AVERAGE CIRCUMFERENTIAL STRAIN AS A FUNCTION OF TIME. THE TEST ENVIRONMENT WAS STEAM/CARBON DIOXIDE (ID/OD).

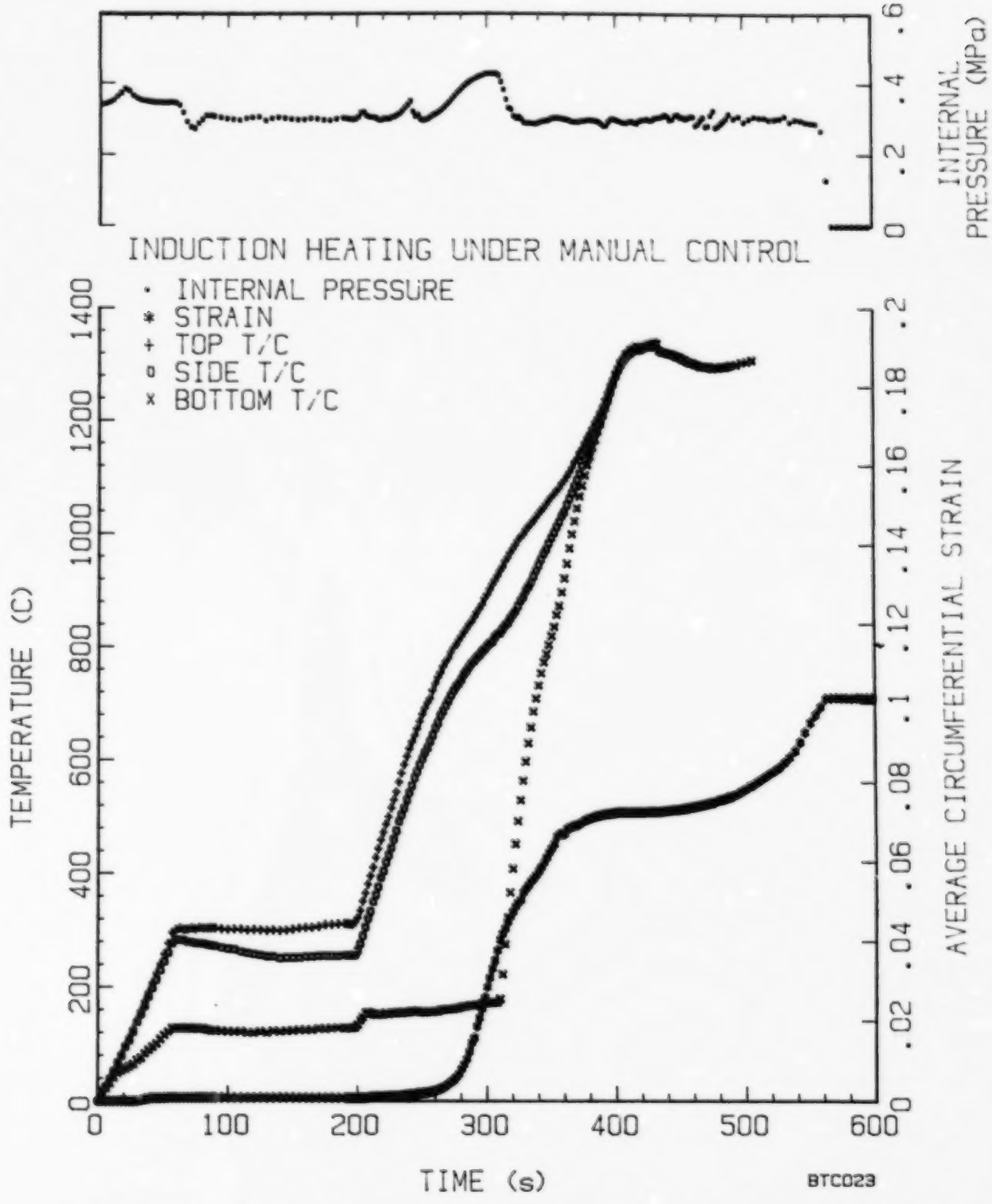


FIGURE 12. PLOTS ILLUSTRATING THE VARIATION OF INTERNAL PRESSURE, SELECTED TEMPERATURES AND AVERAGE CIRCUMFERENTIAL STRAIN AS A FUNCTION OF TIME. THE TEST ENVIRONMENT WAS STEAM/CARBON DIOXIDE (ID/OD). AFTER ABOUT 380 S INTO THE TEST, THE STRAIN DATA ARE UNRELIABLE.

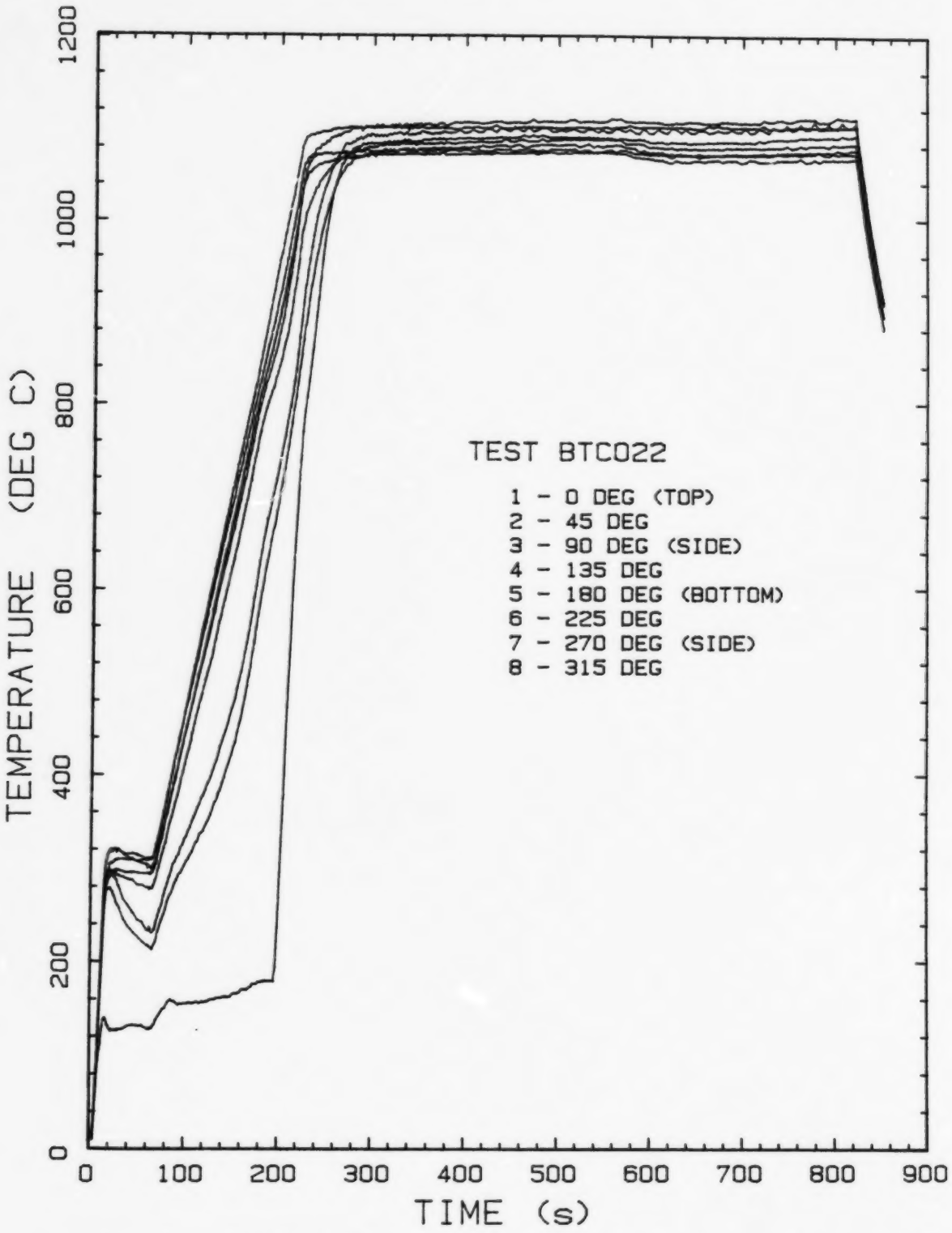


FIGURE 13: PLOTS SHOWING THE DEVELOPMENT OF THE CIRCUMFERENTIAL TEMPERATURE GRADIENT WITH TIME IN THE IMMEDIATE VICINITY OF STRAIN MEASUREMENT IN DETAIL IN TEST BTC022.

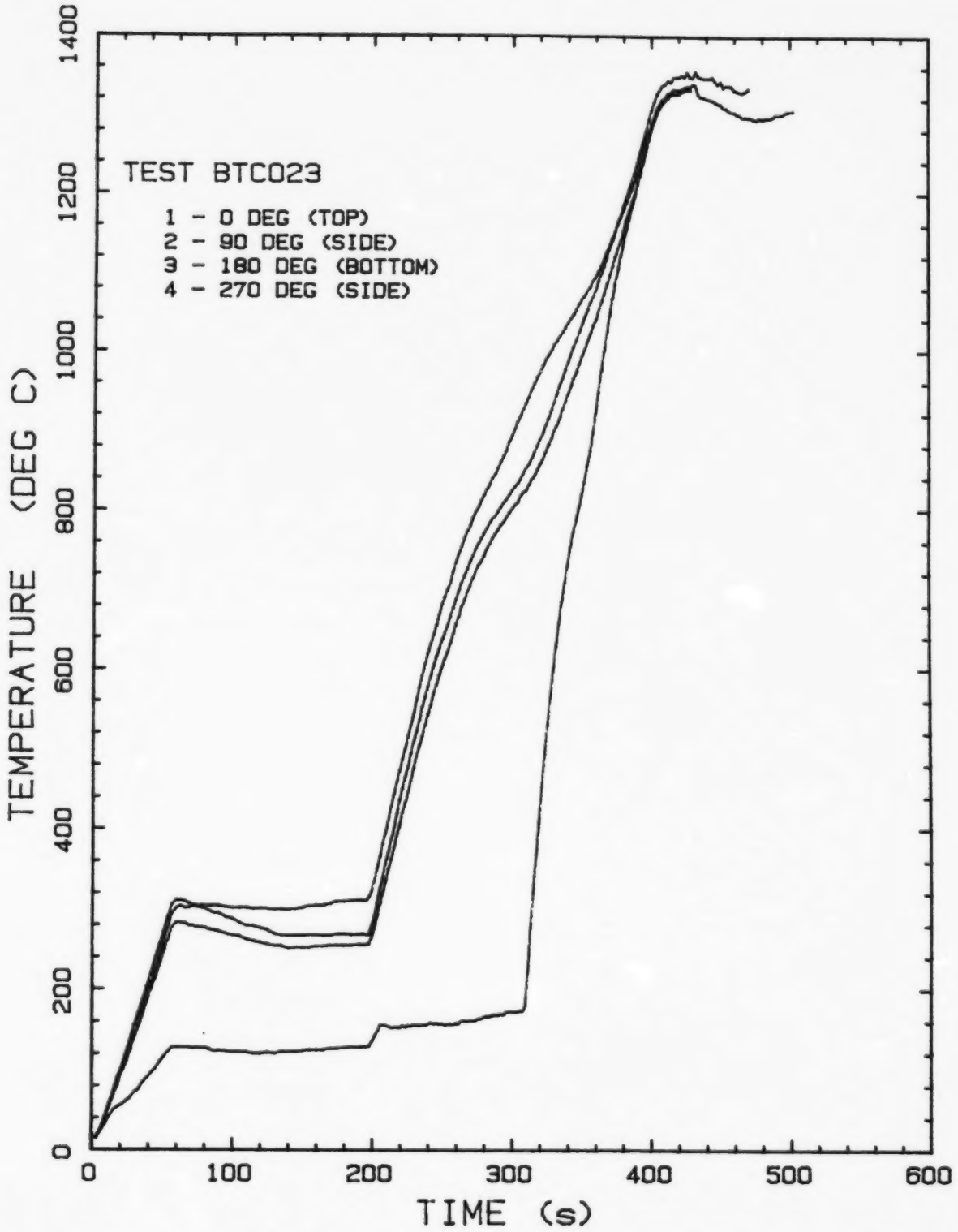


FIGURE 14: PLOTS SHOWING THE DEVELOPMENT OF THE CIRCUMFERENTIAL TEMPERATURE GRADIENT WITH TIME IN THE IMMEDIATE VICINITY OF STRAIN MEASUREMENT IN DETAIL IN TEST BTC023.

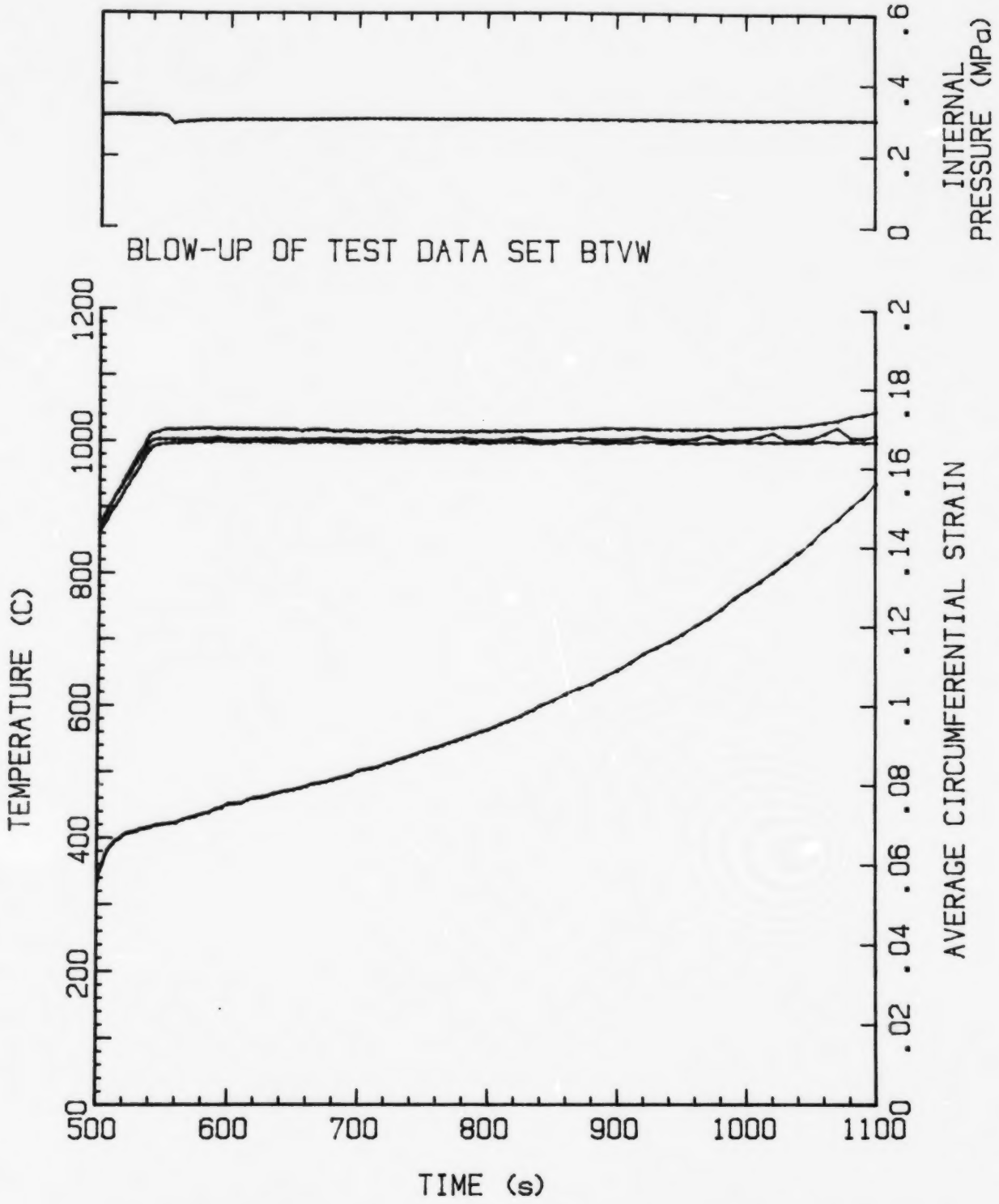


FIGURE 15: BLOW-UP OF TEST DATA SET BTVW. THE BIAXIAL CREEP STRAIN VS TIME CURVE EXHIBITS SECONDARY AND TERTIARY CREEP REGIONS.

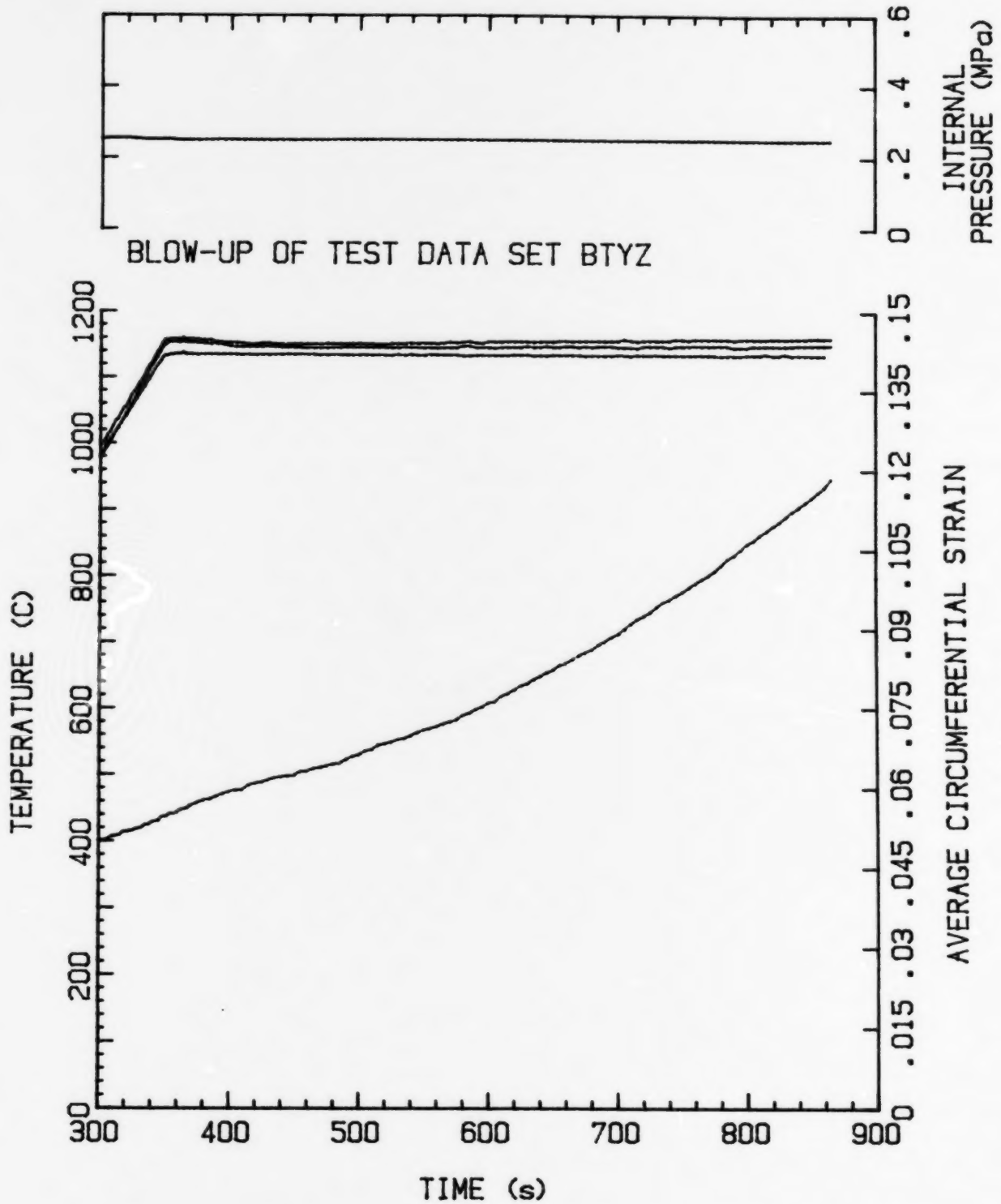

BLOW-UP OF TEST DATA SET BTYZ
INTERNAL PRESSURE (MPa)
0 .2 .4 .6
TEMPERATURE (C)
0 200 400 600 800 1000 1200
AVERAGE CIRCUMFERENTIAL STRAIN
0 .015 .03 .045 .06 .075 .09 .105 .12 .135 .15
300 400 500 600 700 800 900
TIME (s)

FIGURE 16: BLOW-UP OF TEST DATA SET BTYZ. THE BIAXIAL CREEP STRAIN VS TIME CURVE EXHIBITS PRIMARY, SECONDARY AND TERTIARY CREEP REGIONS.

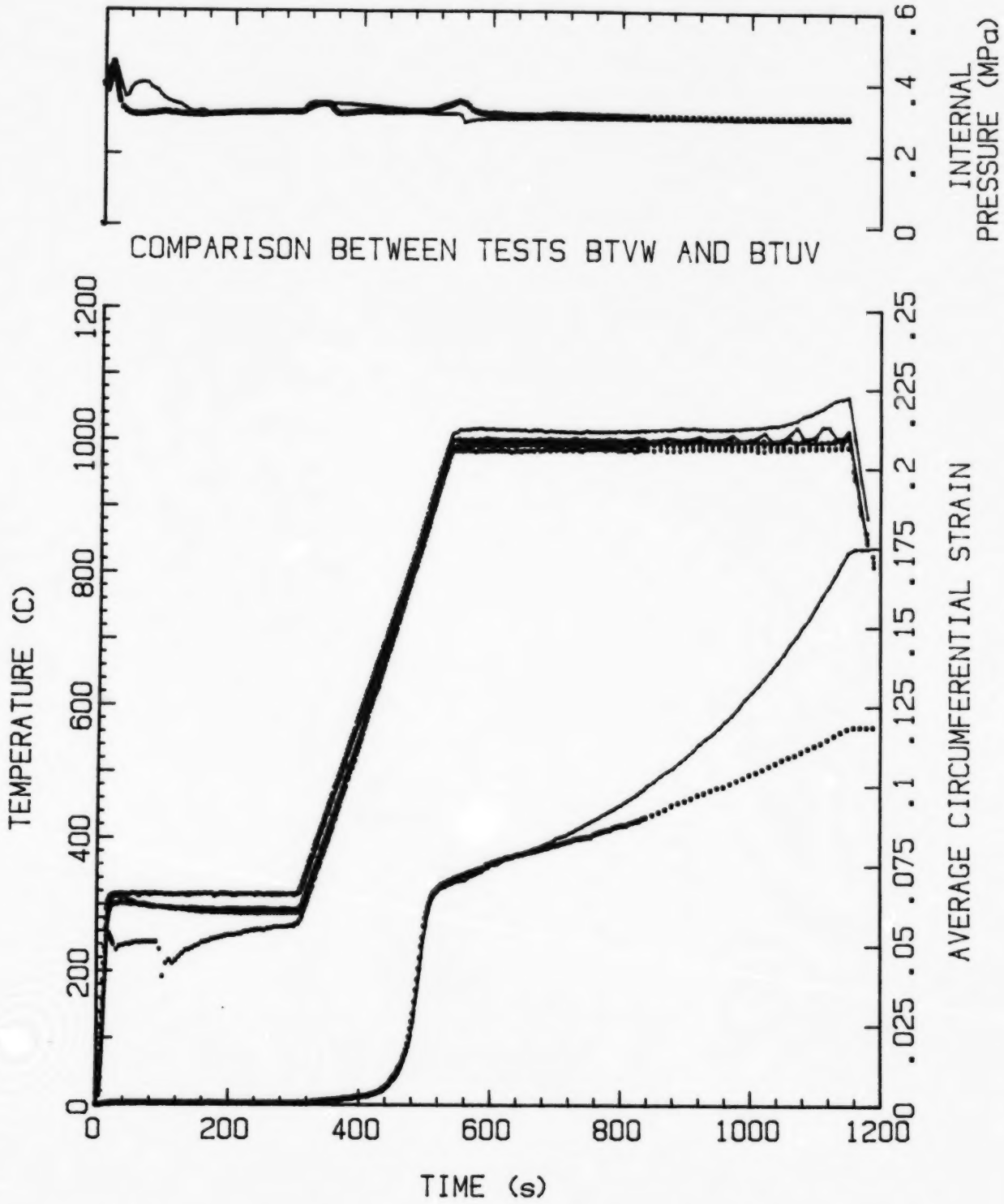

COMPARISON BETWEEN TESTS BTVW AND BTUV
INTERNAL PRESSURE (MPa)
0 .2 .4 .6
TEMPERATURE (C)
0 200 400 600 800 1000 1200
AVERAGE CIRCUMFERENTIAL STRAIN
0 .025 .05 .075 .1 .125 .15 .175 .2 .225 .25
0 200 400 600 800 1000 1200
TIME (s)

FIGURE 17: PLOTS SHOWING A DETAILED COMPARISON BETWEEN DATA SETS BTVW (SOLID CURVES) AND BTUV.

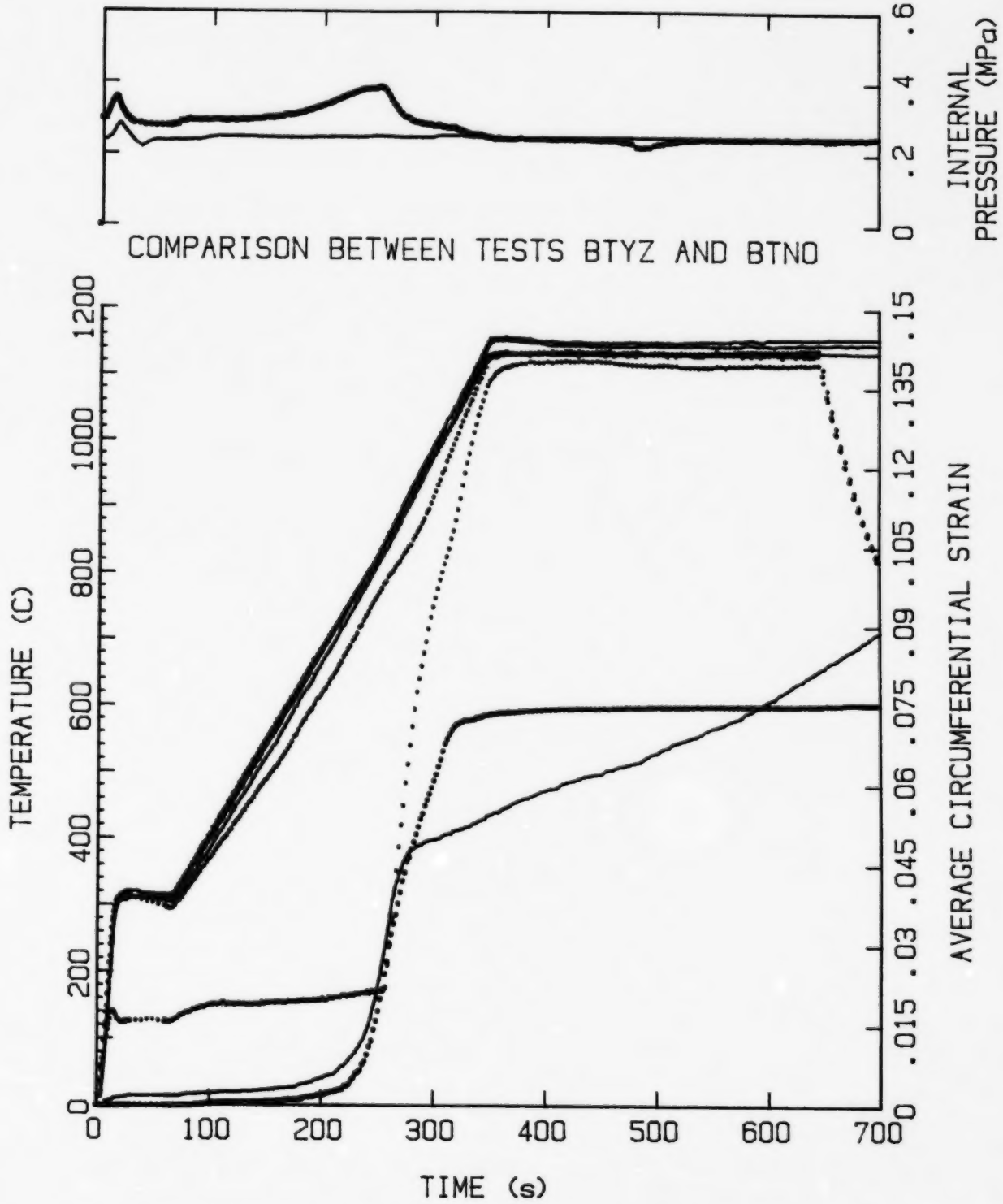

COMPARISON BETWEEN TESTS BTYZ AND BTNO
INTERNAL PRESSURE (MPa)
0 .2 .4 .6
TEMPERATURE (C)
0 200 400 600 800 1000 1200
AVERAGE CIRCUMFERENTIAL STRAIN
0 .015 .03 .045 .06 .075 .09 .105 .12 .135 .15
0 100 200 300 400 500 600 700
TIME (s)

FIGURE 18: PLOTS SHOWING A DETAILED COMPARISON BETWEEN DATA SETS BTYZ (SOLID CURVES) AND BTNO.

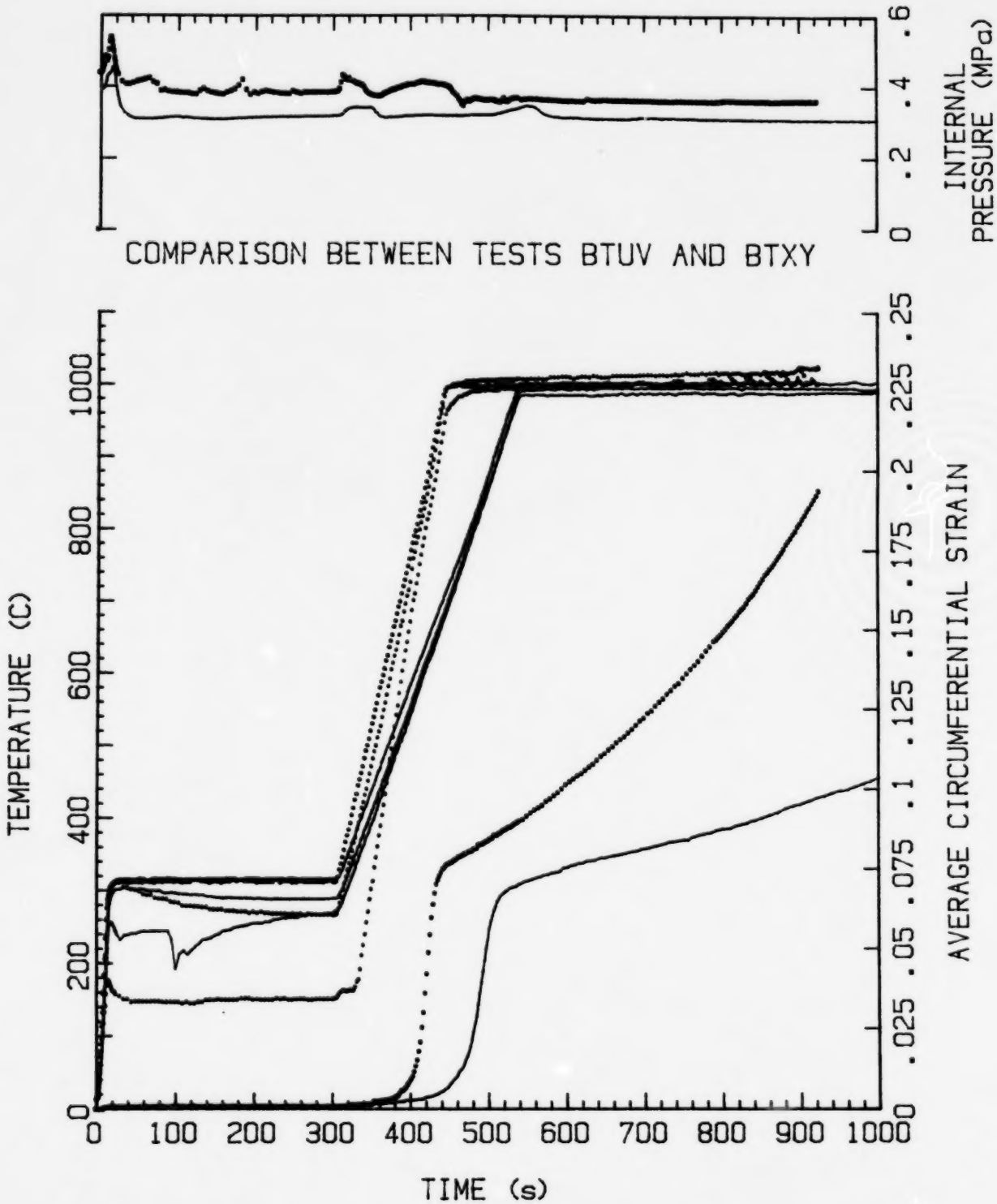

COMPARISON BETWEEN TESTS BTUV AND BTXY
INTERNAL PRESSURE (MPa)
0 .2 .4 .6
TEMPERATURE (C)
0 200 400 600 800 1000
AVERAGE CIRCUMFERENTIAL STRAIN
0 .025 .05 .075 .1 .125 .15 .175 .2 .225 .25
0 100 200 300 400 500 600 700 800 900 1000
TIME (s)

FIGURE 19: PLOTS SHOWING A DETAILED COMPARISON BETWEEN DATA SETS BTUV (SOLID CURVES) AND BTXY.

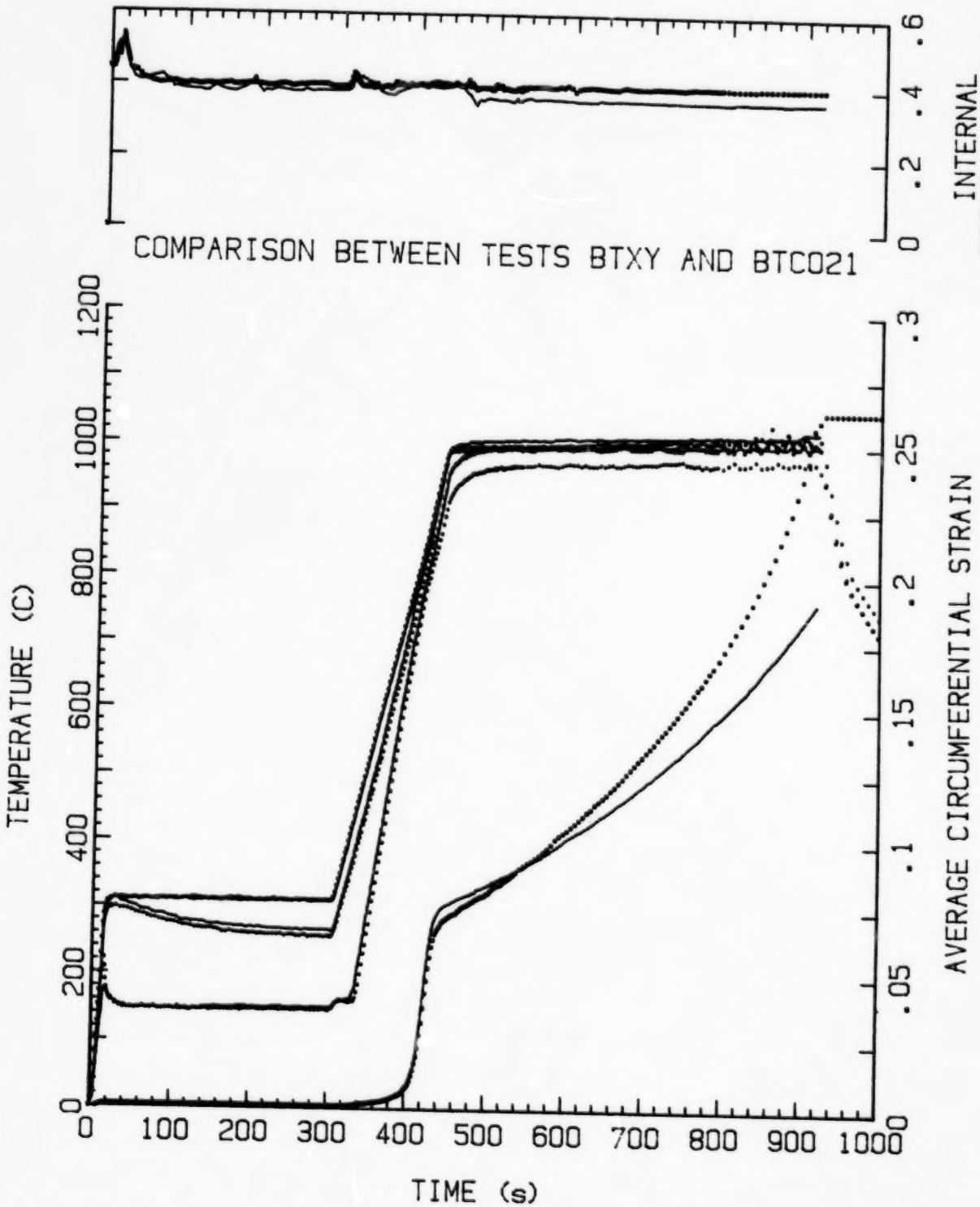


FIGURE 20: PLOTS SHOWING A DETAILED COMPARISON BETWEEN DATA SETS BTXY (SOLID CURVES) AND BTC021.